Energy is conserved in spring-like poppers

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This experiment investigates energy conservation in spring-like popper toys. A popper was compressed and released to obtain its maximum height, its velocity right after hitting the maximum height, and its velocity upon release for five trials. The kinetic energy equation and the potential energy equation were evaluated with the obtained values, where the average of the yielded kinetic energy and potential energy values, 0.068 94 J and 0.079 22 J, respectively, were compared and found to be approximately equal. The elastic potential energy stored in the popper before launch was 0.257 J, further supporting the idea that energy is conserved. A paired t-test comparing the average kinetic energy at launch and the average gravitational potential energy at maximum height for a popper for five trials yielded $p = 0.424$, revealing no statistically significant difference between the kinetic energy at launch and the potential energy at the popper's highest point. This means that the kinetic energy at launch and the potential energy at maximum height are close enough to be comparable, further supporting the idea that energy is conserved.

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I. INTRODUCTION

Kinetic energy (KE) is the energy inside a moving object that makes it move, and can be calculated by the kinetic energy equation [1–3]:

$$KE = \frac{1}{2}mv^2, \quad (1)$$

where m is mass and v is velocity v.

Gravitational potential energy (GPE) is given by [1–3]:

$$GPE = mgh, \quad (2)$$

where m is mass, h is height above some reference height, and $g = 9.8\,\mathrm{m\,s^{-2}}$ is the acceleration of gravity.

We hypothesize that energy is conserved in a frictionless environment, meaning that the total energy of the system should remain constant. Friction was neglected to simplify the experiment, as it has no significantly large impact on the data. The kinetic energy of the system just as the popper left the ground, and the gravitational potential energy of the system at the popper's maximum height were calculated with (1) and (2), respectively, where the system consists of the popper.

The null hypothesis and alternative hypothesis are listed below:

$$H_0 : KE = GPE, \quad (3)$$
$$H_1 : KE \neq GPE. \quad (4)$$

H_0 states that energy is conserved during the popper's motion, meaning the kinetic energy at launch is equal to the gravitational potential energy at maximum height. This would imply that there is no significant difference between the kinetic energy at launch and the potential energy at the popper's maximum height. Alternatively, H_1 states that energy is not conserved during the popper's motion, meaning the kinetic energy at launch is not equal to the gravitational potential energy at maximum height.

To test our hypotheses, we captured video kinematics and analyzed them using methods similar to [4]. FizziQ [4, 5] was used to compute the popper's velocity as it left the initial position $y = 0$ for (1). The initial gravitational potential energy U_0 was defined as zero for all calculations to represent the absence of energy in the system at rest. Since the conservation of energy indicates that there can only be as much kinetic energy as there was potential energy, it was deduced that, if these two values are equal when friction is negligible, energy is conserved. If the two values are not equal, it could indicate energy is not conserved; or more likely that signficant frictional mechanisms need to be accounted for.

II. METHODS AND MATERIALS

A. Popper launches

The popper (Liberty Imports "Jumping Gens"; Allentown, PA) is a yellow, spring-like toy that consists of a ethylene vinyl acetate (EVA) foam head with a conically structured netting attached to it, shown in Fig. 1, with a height of 0.085 m and a mass of 0.0055 kg. The measuring device consisted of two meter sticks that were taped together so that the bottom stick would end at the 0.50 m mark of the top stick. This assembly was propped up by a group member's hands, with the edge

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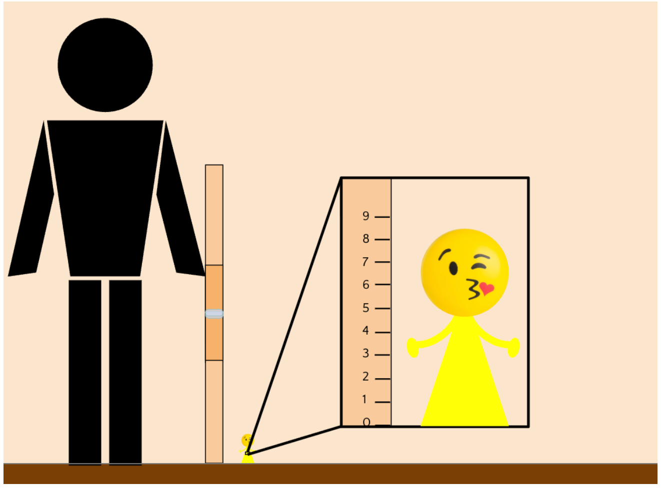

FIG. 1. Setup for the experiment depicting the measuring device and the popper; not to scale.

FIG. 2. Setup for the mechanical work portion of the experiment showing digital scale, popper, and scissor jack. Popper is shown at onset of snap-through instability.

of the ruler staying flat on the ground. Then, a popper was pinched between another group member's thumb and index finger at the side of the foam head to compress it toward $y = 0$, the popper's snap-through point. To release the popper, the thumb and index finger were simultaneously removed from the foam head, allowing the popper to spring upwards and reach its maximum height before moving downwards. For a total of five trials, the same person released each popper with this method for each trial to avoid confounding variables. The popper's maximum height from each trial was documented through visual observation and later, more precisely observed in videos of each trial taken at 60 frame/s with an iPhone 15 (Apple, Inc; Cupertino, CA). These videos were then processed through FizziQ, where each frame was handpicked, and the popper's position was indicated with a point and positioned by a group member [4, 5]. To find the velocity and maximum height with the FizziQ app, each video of each trial was input into the software [5]. After setting the initial position $y = 0\,\mathrm{m}$ and time $t = 0\,\mathrm{s}$, appropriate times during the video were selected that allowed for accurate pinpointing of the position of the popper at that time (see Table I). The experiment was conducted inside a classroom in a secluded area with the windows closed, unaffected by external factors and elements, such as other individuals and wind.

B. Work to compress a popper

To measure the work done in compressing a popper before release, a digital scale (TOP2KG; Smart Weigh; Jiangsu, China) was placed under the popper to measure the mass in grams, and zeroed to avoid counting the popper's deadweight, as shown in Fig. 2. The scissor jack was placed next to the scale so that the platform sat on the popper's foam head. The scissor jack was used to adjust to a specific compression height for each trial, allowing for more exact calculations of force measurements. Additionally, the use of this tool avoided confounding variables like inconsistent human force or human error when handling the popper. With this setup, the scissor jack's platform was lowered, thereby compressing the popper to find more precise measurements of force without human error, shown in Fig. 3. The scale reading was later converted to N using $F = mg$, where $g = 9.8\,\mathrm{m\,s^{-2}}$. The force versus displacement was plotted an a trapezoidal integration method used to determine the work done during launch [6–8].

III. RESULTS

A. Work to compress a popper

Fig. 3, shows the spring force generated by different compression distances. From this, the elastic potential energy stored in the popper before release was calculated as the area under the curve. At the snap-through point, a distance of 0.05 m compressed, the area under the curve was approximately 0.257 J.

B. Popper launches

Table I provides representative kinematics data from FizziQ based on a trial video [5]. Table I shows the maximum height and velocity upon release for each trial. Corresponding values for all trials are compiled in in Table II.

In Table III, the kinetic energy of the system at the moment of release and the potential energy of the system at

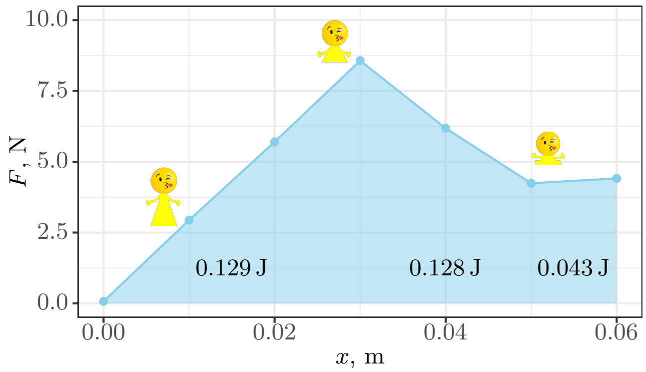

FIG. 3. Graph showing the force in N generated at different compression distances in m. Between 0.03 m and 0.05 m shows the popper's snap-through in which the spring curvature direction reverses. The respective elastic potential energies at 0.03 m, 0.05 m, and 0.06 m are shown as areas under the curve.

TABLE I. One of the tables created by FizziQ, based on a video of the first trial with selected values to be shown, such as the vertical position (height) and the velocity [5]. The maximum height, velocity upon release, and velocity right after hitting the maximum height are marked with a star. The cells without values are intentionally left blank.

t, s	h, m	v, m s^{-1}
0	0.03	
0.03	0.19	* 5.63
0.07	0.39	5.38
0.10	0.57	5.05
0.13	0.71	4.42
0.16	0.85	3.81
0.19	0.96	3.14
0.42	** 1.39	** 0.83
0.68	1.27	

* upon release
** at maximum height

TABLE II. Maximum height, velocity upon release, and velocity at maximum height for each trial

trial	h, m	v_0, m s^{-1}	$v(h)$, m s^{-1}
1	1.39	5.63	−0.83
2	1.41	5.80	−0.38
3	1.54	5.45	−0.22
4	1.42	2.94	−0.10
5	1.63	4.69	−0.13

TABLE III. Kinetic energy upon release, kinetic energy at maximum height, potential energy at maximum height, and the difference between

trial	KE_0, J	$KE(h)$, J	$GPE(h)$, J	$KE_0 - GPE$, J
1	0.086	1.86×10^{-3}	0.074	0.012
2	0.091	3.80×10^{-4}	0.080	0.011
3	0.080	1.31×10^{-4}	0.082	0.002
4	0.028	0.27×10^{-4}	0.074	0.047
5	0.059	4.88×10^{-4}	0.086	0.027

the popper's maximum height were compared. It is important to note that, in Table II, the fourth trial shows a significantly lower velocity than the others, at 2.94 m s^{-1}. This is most likely due to human error, inconsistent release of the popper, or inaccuracy with measurements. This outlier contributed to the overall decrease in kinetic energy and the lower t-statistic.

IV. DISCUSSION

A. Energy is conserved during popper launches

This experiment provides experimental confirmation that energy is conserved when friction is negligible. Although limited by human and experimental error, a general idea for energy conservation was established. As shown in Table III and Fig. 4, the difference between KE and PE was slightly higher than anticipated, with an average difference of about 0.020 J. The data showed a similarity of approximately ±0.1 J between the initial kinetic energy and potential energy at the peak of the launch, averaged across the five trials. This consistency demonstrates that energy was conserved, although any discrepancies may be attributed to limitations of the FizziQ app and human error when releasing the poppers [5]. A significant limitation was that it could not accurately capture the exact moment when the popper began its upward motion, instead registering a few milliseconds later.

A paired t-test was performed to compare the kinetic energy at launch and the potential energy at the popper's maximum height with the values in Table III. As shown, the analysis yielded a t-statistic of $t = -0.89$ and a two-tailed p-value of $p = 0.424$. Since $p = 0.424 > \alpha = 0.05$, there was no statistically significant difference between the kinetic energy at launch and the potential energy at the popper's highest point. This means that energy is conserved within the popper's flight.

Furthermore, the calculated elastic potential energy was 0.257 J, which appears far from the average kinetic energy and potential energy values. A significant amount of energy is lost upon release, especially due to friction between the popper's conical netting. Assuming that

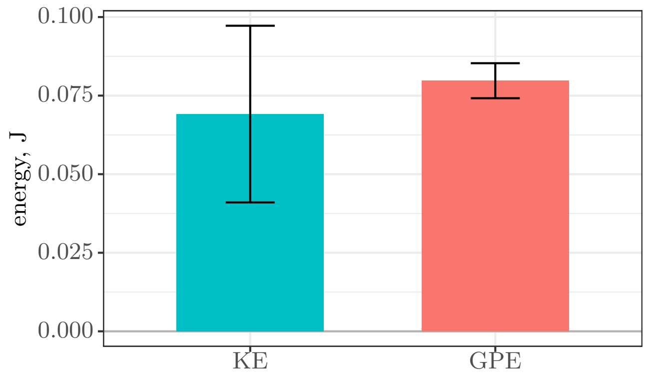

FIG. 4. A bar graph comparing the two primary energy states with standard deviation error bars. Note that KE's error bar length is much larger than GPE's due to Trial 4 (an outlier), which had a much lower velocity of 2.94 m s^{-1}, thus significantly increasing the standard deviation for the KE measurements.

about 73.2 % of the elastic potential energy was lost to friction, heat, and sound, the rest of the elastic potential energy was converted to kinetic energy, which forced the popper upwards and yielded the first two values in Table III. From these we conclude that the major energy loss mechanisms occur during launch and are associated with the popper material or friction during the launch process; not due to drag or other loss during the flight phase. Furthermore, the value of KE_{max} nears 0 in each trial, implying that the popper's kinetic energy at launch was near or completely depleted by the time the popper reached its maximum height. This further supports energy conservation, as the kinetic energy at launch was converted into other energy types, gravitational potential energy being the most prominent, as shown by the close values of KE_r and GPE.

B. Sources of experimental error

Friction was neglected throughout this experiment, but it would still affect the popper as it traveled through the air, contributing to experimental error. In addition to environmental factors, many errors can also be attributed to human error, as visual observation and 60 frame/s videos are not always sufficient in accurately describing exact points, and manual compression and release were likely somewhat biased by the human releaser's reaction time. Future experiments could be improved by performing the experiment in a vacuum, where air resistance is actually negligible, measuring data by more accurate means, such as with high-speed cameras, and using more precise methods of compression and release.

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